An Observing System Simulation Experiment for the Unmanned Aircraft System Data Impact on Tropical Cyclone Track Forecasts

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ABSTRACT

High-altitude, long-endurance unmanned aircraft systems (HALE UAS) are capable of extended flights for atmospheric sampling. A case study was conducted to evaluate the potential impact of dropwindsonde observations from HALE UAS on tropical cyclone track prediction; tropical cyclone intensity was not addressed. This study employs a global observing system simulation experiment (OSSE) developed at the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL) that is based on the NOAA/National Centers for Environmental Prediction gridpoint statistical interpolation (GSI) data assimilation system and Global Forecast System (GFS) model. Different strategies for dropwindsonde deployment and UAS flight paths were compared. The introduction of UAS-deployed dropwindsondes was found to consistently improve the track forecast skill during the early forecast up to 96 h, with the caveat that the experiments omitted both vortex relocation and dropwindsondes from manned flights in the tropical cyclone region. The more effective UAS dropwindsonde deployment patterns sampled both the environment and the body of the tropical cyclone.

1. Introduction

Dropwindsonde observations in the vicinity of tropical cyclones (TC) have been found to be effective in improving short-range (1–3 day) forecasts of the TC track shortly prior to their landfall (Aberson 2010; Majumdar et al. 2011). However, they have not been targeted for longer forecast ranges, partly due to the limited range of manned aircraft. High-altitude, long-endurance unmanned aircraft systems (HALE UAS) have long flight duration capabilities that enable the aircraft to reach TCs that are too far from land for manned aircraft missions. If multiple UAS were available, a TC could be continuously monitored, possibly offering additional benefits. The HALE UAS capabilities for long-endurance missions and use of a pod to remotely deploy dropwindsondes to observe TCs have recently been demonstrated as part of the National Aeronautics and Space Administration (NASA) Genesis and Rapid Intensification Processes (GRIP; Braun et al. 2013) field experiment and the Hurricane and Severe Storm Sentinel (HS3) mission.

Recently, an observing system experiment by Majumdar et al. (2013) found that dropwindsondes deployed from manned aircraft resulted in up to 20% improvements of the 2–3-day track forecasts for Hurricane Irene (2011), but the optimal sampling strategies for HALE UAS may differ from those employed for manned aircraft. Since it would be difficult to make a clean comparison of different flight and sampling strategies using real observations because of the limited availability of both the UAS platforms and the infrequent presence of suitable TCs for study, an observing system simulation experiment (OSSE) approach is used here.

In this study, a global OSSE system codeveloped by the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL), the

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European Centre for Medium-Range Weather Forecasts (ECMWF), the National Centers for Environmental Prediction (NCEP), and several other institutions (Andersson and Masutani 2010) is used to evaluate the potential impact of HALE UAS observations on TC track forecasts using a case study in the Atlantic basin. Several different flight patterns and sampling strategies are tested including both single UAS missions and continuous monitoring by multiple UAS. Section 2 describes the OSSE setup and experimental methodology. In section 3, the results of the case study are shown, with a discussion of the results in section 4.

2. Methodology

The global OSSE consists of a nature run (NR) that acts as "truth," a set of synthetic observations derived from the NR, and the data assimilation system and model used to generate the experimental forecasts. The setup and calibration of this OSSE system are described in detail in Privé et al. (2013).

The NR is a free forecast of the ECMWF operational model (version c31r1) at T511 spectral resolution with 91 levels (Andersson and Masutani 2010), started at 1200 UTC 1 May 2005 and integrated through 1200 UTC 1 June 2006. Evaluation of the NR shows that hurricane tracks in the Atlantic basin are realistically depicted (Reale et al. 2007).

Simulated observations for the global observational network were created by the NASA Global Modeling and Assimilation Office (GMAO) and by the NCEP Environmental Modeling Center (EMC). The method used to generate the observations makes use of the spatial and temporal distribution of satellite and conventional observations actually made in 2005–06 to determine the location and times to interpolate from the NR fields (Errico et al. 2013). The simulated observations include radiance data for the Atmospheric Infrared Sounder (AIRS), Advanced Microwave Sounding Units (AMSU-A and AMSU-B), High Resolution Infrared Radiation Sounders (HIRS-2 and HIRS-3) produced by GMAO, and conventional data and radiance data for the Geostationary Operational Environmental Satellite (GOES) and the Solar Backscatter Ultraviolet Radiometer (SBUV) produced by EMC. Simulated observations for UAS were generated at ESRL by simulating the flight of the UAS through the NR. The flight path of the UAS is given as a series of prescribed waypoints, with a simulated dropwindsonde released at each waypoint, and the advection of the falling sonde calculated using the NR wind field, although the gridpoint statistical interpolation (GSI) does not account for this advection. Observation errors were added to the synthetic observations as described by Errico et al. (2013) and Privé et al. (2013).

The operational Global Forecast System (GFS) model version from spring 2007 is used for experimental forecasts at T382 resolution with 64 vertical levels. The GFS is coupled to the operational GSI data assimilation system (Kleist et al. 2009). Calibration of the OSSE (Privé et al. 2013) showed that forecast skill in the OSSE was comparable to skill of forecasts using real data.

3. Case study

The case study examines forecast track skill for the first Atlantic basin storm in the NR, denoted AL01, which follows a recurving track in the western Atlantic from 1 August to 11 August. A set of Control forecasts is generated by cycling the GSI/GFS over the lifespan of AL01, generating a 120-h forecast every 6 h, and using only the standard observational dataset with no additional dropwindsondes. The Control data assimilation begins one week prior to 1 August and continues to assimilate the standard set of observations through 7 August. The Control forecasts capture the characteristics of the true track throughout the life cycle of AL01, and in most cases the track errors are small.

In the first set of experiments, a single UAS mission samples the TC, with additional dropwindsonde observations ingested only for a small number of data assimilation (DAS) cycles. These single flight tests are used to evaluate the impact of different flight paths and sampling methods on forecast skill. In a second set of tests, it is assumed that multiple UAS would be available to continuously monitor the TC for several days. In these tests, only one sampling strategy is used, but forecast skill at different times in the life cycle of the TC is examined.

For all GFS forecasts, the storm track was calculated using the Geophysical Fluid Dynamics Laboratory (GFDL) vortex tracker. To avoid modifying the vortex tracker to read the NR data on a reduced Gaussian grid, the true track of AL01 in the NR was determined by manually locating the central surface pressure minima.

Tropical Cyclone Vitals (TCVitals) data are generated by forecasters during real-time forecasting to provide an estimate of tropical cyclone location and strength for use in vortex relocation (Trahan and Sparling 2012). Because of the complexity of the process of creating these data, the TCVitals data (including suitable errors) are not easily replicated in the OSSE system, and, therefore, the relocation processes were omitted. This results in larger position errors at the analysis time in the OSSE compared to typical operational practice where vortex relocation is used. Likewise, dropwindsondes from manned flights were excluded, although dropwindsonde data within 150 km of the vortex center were not ingested operationally in this model version (Aberson 2008), so this omission is expected to have a smaller impact on results than the neglect of vortex relocation.

a. *Single flight path tests*

For the single flight path tests, forecast periods are chosen that have the greatest error in the Control experiment, so that there is the greatest opportunity to clearly discern any positive impact of additional observations. The errors for these forecasts from 1200 UTC 5 August and 0000 UTC 6 August are shown in Table 1.

In this study, a HALE UAS flies in circles around the moving center of the hurricane at various radii and releases a dropwindsonde every 105 km along the flight path. Several different flight patterns were tested as illustrated in Fig. 1. For comparison, the operational observing strategy used by the National Hurricane Center requires the sampling of dropwindsondes around the entire TC, with additional dropwindsondes deployed either subjectively (based on synoptic reasoning) or in areas of large ensemble spread.

HALE UAS might have flight endurance sufficient to fly the same flight pattern repeatedly during a single mission. If a flight pattern *N* is repeated twice during the mission, the flight path name is *NN*, or *NNN* if the pattern is repeated three times. Table 2 describes the total flight time (excluding travel to and from the TC), the number of dropwindsondes deployed, and the time at which the first dropwindsonde is deployed in the single flight OSSE experiments. Flight patterns with traversal times of greater than 12 h were not repeated. The sampling strategies were not limited to the current capabilities of a particular operational mission (e.g., the Global Hawk outfitted with an 88-dropwindsonde pod), as new platforms with different capabilities are under development.

Table 1 shows the forecast error as a function of forecast hour for each of the tested flight paths. Flight paths AA and AAA yield identical results for the 1200 UTC 5 August forecast as there is no difference in available dropwindsonde observations in the two cases prior to 1700 UTC 5 August, but flight path AAA reduces errors compared to the AA case for the 0000 UTC 6 August forecast. The impact of the UAS sonde data on the analysis field is primarily seen within a 1000-km radius of the storm center in these experiments (not shown). The 1200 UTC 5 August forecast shows decreased error at all forecast times compared to Control, but the 0000 UTC 6 August forecast shows increased error after 72 h.

The flight paths with larger radii of observations (BB, C, and D) show greater forecast improvement for the 1200 UTC 5 August forecast than the flight paths with smaller radii (AA, AAA). In the C and D experiments, the hurricane vortex is weaker in the analysis compared to the AA and AAA experiments, presumably due to lack of observations of the inner storm. However, in all of the BB, C, and D experiments, the 500-hPa poleward flow to the north of the storm in the analysis is weaker than in the Control, AA, and AAA experiments (not shown) as a result of the dropwindsonde observations at large radii. This difference in the steering flow in the analysis is consistent with the improvement in the track forecast.

TABLE 1. Forecast track errors for single flight path experiments (km). Boldface values indicate improvement in the UAS case compared to Control of greater than 10%; italicized values indicate worsening in the UAS case of greater than 10%.

Forecast start	Expt	Analysis	24 h	48 h	72 h	96 h	120 h
1200 UTC 5 Aug	Control	108	127	170	264	367	692
	AA	**67**	**92**	171	**210**	347	635
	AAA	**67**	**92**	171	**210**	347	635
	BB	**67**	**84**	171	**210**	347	635
	C	**70**	**30**	**127**	**164**	**293**	**405**
	D	103	**38**	**121**	**183**	**293**	**445**
0000 UTC 6 Aug	Control	52	137	253	290	361	676
	AA	**30**	**115**	**216**	278	391	*801*
	AAA	**30**	**91**	**184**	**240**	369	*765*
	BB	**0**	**51**	**191**	**240**	*400*	*772*
	C	**39**	**80**	**196**	286	361	705
	D	**44**	**119**	**203**	285	393	725

The forecast hurricane tracks show slight improvement in the along-path track error when UAS dropwindsondes are included, but little improvement in the cross-track error—the main effect of the UAS observations is to slow the northward progression of the storm during the first few days of the forecast. This is illustrated in Fig. 2, where the experiment C forecast tracks have a more westward bias than the Control from 48 to 96 h.

For the AL01 Control case, there are two forecast scenarios involving the interaction of the TC with a synoptic midlatitude wave that passes over New England. In the first scenario, which is what occurs in the NR, the TC has little interaction with this synoptic wave, and maintains a relatively slow progression as it recurves over the western Atlantic. In the second scenario, which occurs in most of the Control forecasts, however, the TC has greater interaction with the passing wave resulting in a more rapid acceleration of the TC during recurvature. While the additional dropwindsonde observations and especially those at larger radii are helpful in slowing the initial progress of the TC in the forecasts starting at 1200 UTC 5 August and 0000 UTC 6 August, there is still too much interaction with the synoptic wave during the later forecast times.

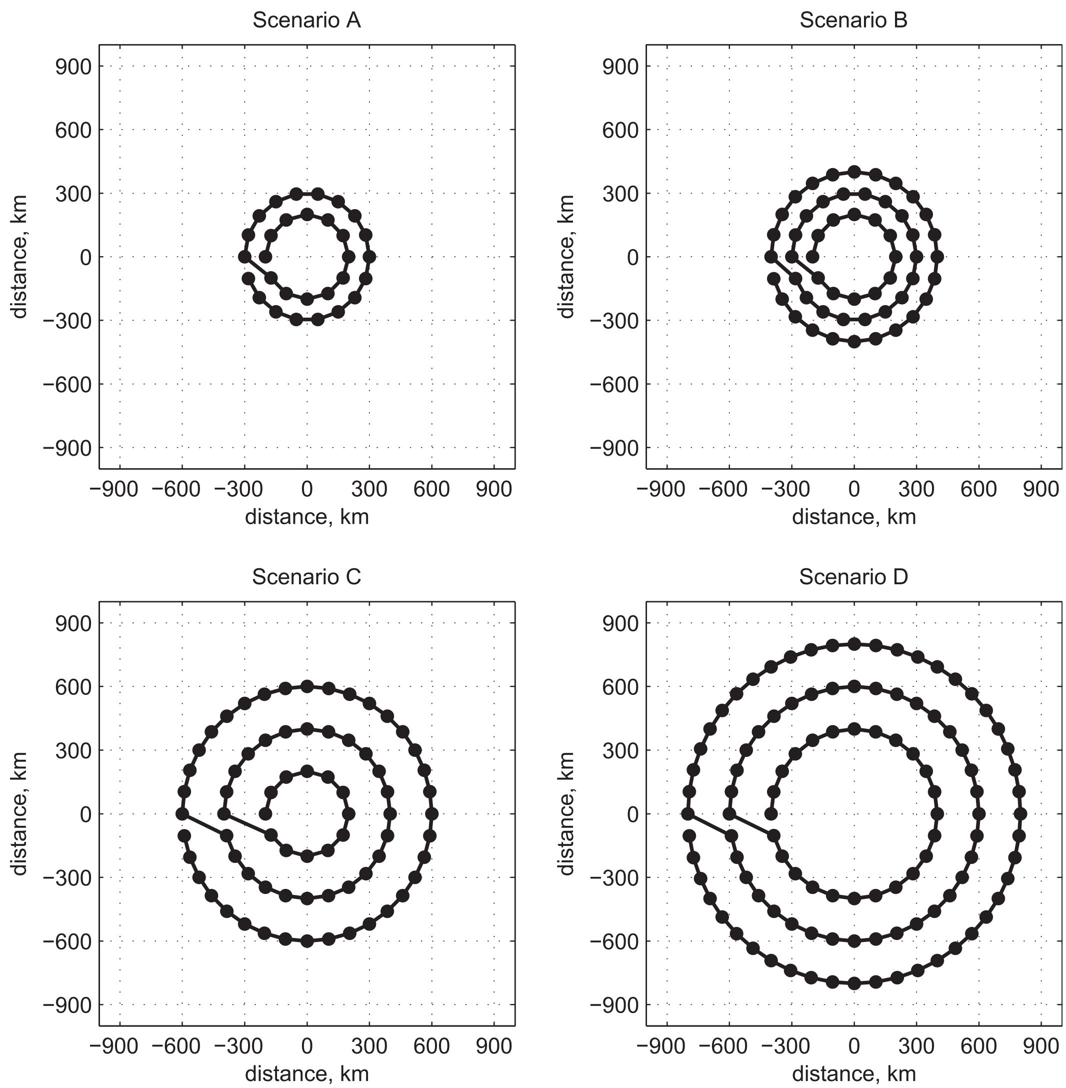

FIG. 1. Flight path diagrams. Small filled circles indicate locations of dropwindsonde release points, which are spaced every 105 km along each flight pattern.

b. Continual monitoring

The best performing flight pattern from the single flight path experiments—flight pattern C—is chosen for use in the continual monitoring cases. Continual monitoring is initiated at 1200 UTC 1 August and continues until 0000 UTC 7 August, with 833 dropwindsondes deployed during this period (Fig. 3). This test is performed to determine if continual monitoring is more useful than intermittent monitoring, and to extend the case study to a wider range of forecast initial times.

Forecasts are initiated every 12 h from 1200 UTC 1 August to 0000 UTC 7 August, with the forecast track error compared to the Control forecasts shown in Table 3. The results show a decrease in position error in the continual monitoring (CM) experiment compared to Control at the analysis time and 24-h forecast for all forecast cycles. From the 48- to 96-h forecasts, a majority of CM forecasts have less error than Control, but at 120 h there is not a consistent improvement in the CM

TABLE 2. Single flight path experiment details.

Expt	First observation (UTC time and date)	Flight time (h)	No. of dropwindsondes
AA	0600 UTC 5 Aug	11	60
AAA	0600 UTC 5 Aug	16	90
BB	0300 UTC 5 Aug	19	108
C	0600 UTC 5 Aug	13	72
D	0600 UTC 5 Aug	18	108

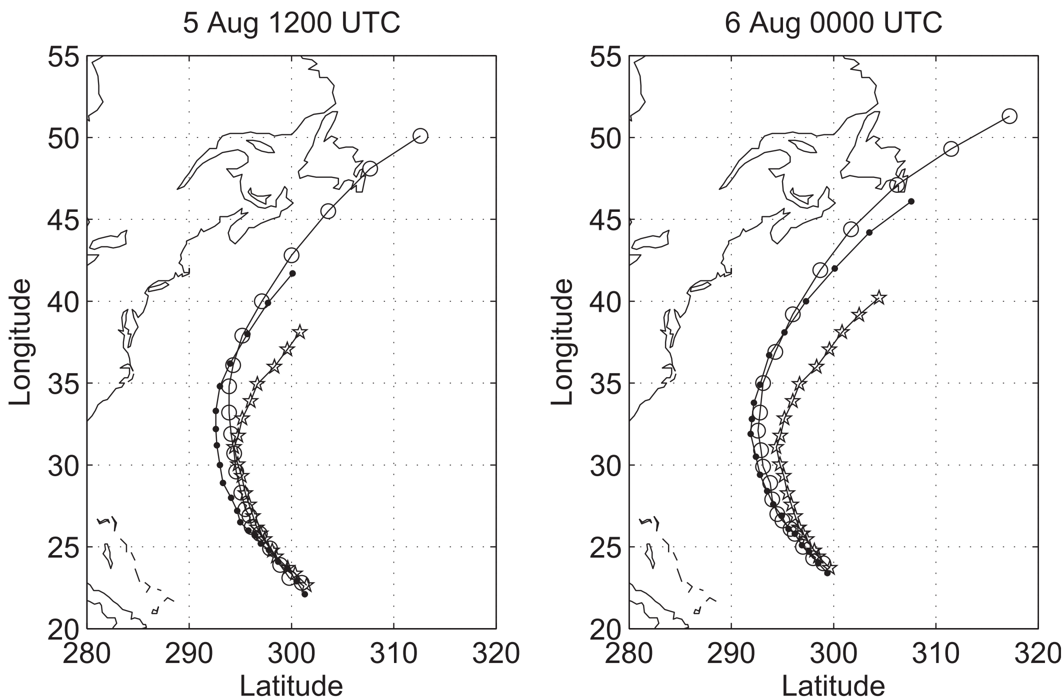

FIG. 2. Forecast tracks compared with the actual track of AL01 for forecasts initialized at (left) 1200 UTC 5 Aug and (right) 0000 UTC 6 Aug. The TC center location is marked every 6 h out to 120 h using stars for the true track, small filled circles for experiment C, and open circles for the Control experiment.

experiment. One particular forecast starting at 0000 UTC 5 August has extremely low forecast error in the Control experiment—only 24-km error at 120 h—while the CM forecast for this initial time has a more typical progression of increasing forecast errors.

The 1200 UTC 5 August and 0000 UTC 6 August forecasts in experiment CM can be compared to the forecasts in Table 1 for experiment C. There is not a substantial difference in the forecast skill at either cycle time during the short-term forecast, but the 120-h forecast error is greater in experiment CM.

4. Discussion

An OSSE study was conducted to examine the impact of dropwindsonde data from HALE UAS on TC track forecasts for the case of an Atlantic basin TC. The first set of experiments examined the impact of observations from a number of possible flight paths that circumnavigate the hurricane and could be planned well in advance of a UAS mission. Sampling both the outer and inner storm regions yielded greater track improvement in comparison to repeatedly sampling only the inner storm environment. This main conclusion is consistent with the results of Harnisch and Weissmann (2010), who showed that TC track forecasts are mostly improved by the assimilation of dropwindsonde observations in the vicinity of the TC (cf. the inner core or the remote environment).

The most consistent improvement in track forecast skill occurred for the short-term forecast, with less improvement in the medium-range forecasts; this decrease of observation impact at longer forecast times is not unexpected in general and especially in this case of a TC interacting with a synoptic midlatitude wave at these forecast times. As the forecast time approaches the limits

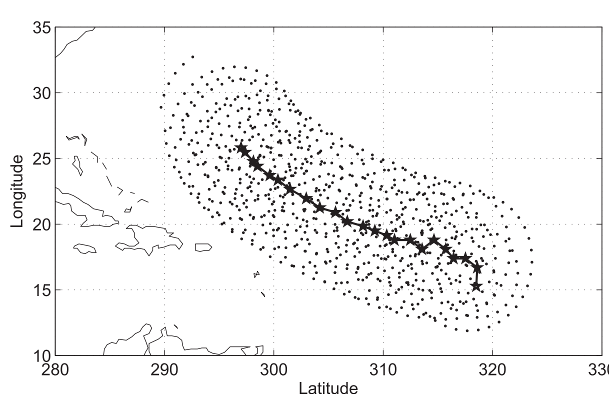

FIG. 3. Location of dropwindsonde deployments from 1200 UTC 1 Aug to 0000 UTC 7 Aug in the CM experiment are plotted as dots. The heavy line indicates the actual track of AL01 during this period, with stars marking the central position every 6 h.

TABLE 3. Forecast track errors for Control and continuous monitoring (CM) experiment (km). Boldface values indicate improvement in the CM case compared to Control of greater than 10%; italicized values indicate worsening in the CM experiment of greater than 10%.

Forecast	Expt	Analysis	24 h	48 h	72 h	96 h	120 h
1200 UTC	Control	94	222	186	283	411	515
1 Aug	CM	89	**110**	**95**	**183**	**258**	**325**
0000 UTC	Control	87	91	81	235	292	289
2 Aug	CM	**69**	**39**	**70**	**186**	**241**	*356*
1200 UTC	Control	91	110	216	249	230	124
2 Aug	CM	**54**	**76**	**118**	**151**	**177**	*312*
0000 UTC	Control	106	170	325	357	290	201
3 Aug	CM	**42**	**25**	**115**	**84**	**63**	**165**
1200 UTC	Control	54	231	342	414	344	351
3 Aug	CM	**11**	**81**	**132**	**124**	**113**	**228**
0000 UTC	Control	128	182	196	237	350	595
4 Aug	CM	**49**	**70**	**53**	**152**	**259**	**469**
1200 UTC	Control	170	155	135	104	115	205
4 Aug	CM	**53**	**33**	**30**	**53**	*208*	*427*
0000 UTC	Control	162	70	83	95	65	24
5 Aug	CM	**10**	**39**	100	*156*	*339*	*928*
1200 UTC	Control	108	127	170	264	367	692
5 Aug	CM	**44**	**52**	**121**	**211**	340	*849*
0000 UTC	Control	52	137	253	290	360	676
6 Aug	CM	**30**	**52**	**152**	**230**	346	*1022*
1200 UTC	Control	40	142	216	374	1262	1810
6 Aug	CM	**10**	**74**	**169**	380	1200	1761
0000 UTC	Control	15	89	87	252	1005	
7 Aug	CM	**11**	**59**	**49**	**52**	**562**	

of predictability, it is expected that impacts for all data types will approach zero. Many initial condition errors are damped, or exhibit neutral or minimal growth during integration of the forecast; only corrections to initial condition errors that grow strongly over a time scale of several days would contribute to observation impacts of medium-range forecasts. The growth of model error as the forecast progresses can also reduce observation impacts. It is a challenge to improve the medium-range track forecasts with sampling only in the vicinity of the TC, and with no additional observations of the upstream steering flow.

Continuous monitoring of the TC resulted in short-term forecast improvement for all forecasts, with mixed results for longer forecasts. The improvement of the forecasts due to more frequent sampling is consistent with Aberson (2010), who suggested that forecasts are improved when the NOAA G-IV aircraft is flown twice per day. Comparing forecast skill between cases where a longer/shorter sampling period is used prior to the analysis time (cf. single flight paths AA and AAA, or the continuous monitoring case to the single flight path C cases) does not show a consistent advantage for the case with longer sampling period. Likewise, the 0000 UTC 6 August forecasts from the single flight path experiments do not show greater overall improvement in track forecasts compared to the 1200 UTC 5 August forecasts, although the 6 August forecasts should benefit from having improved background states unlike the 5 August forecasts. This implies that the observations that most benefit the skill of an individual forecast of TC track are those assimilated into the analysis state of that forecast, and that the cumulative impact of observations over multiple analysis cycles is relatively small. This is not unexpected for a localized observing network, whereas cumulative improvements in the background state due to a large-scale observing network might be expected to have a more significant impact. This result is specific to the case of TC track forecasts, where the cyclones are steered by large-scale flow, and is not generally applicable to other phenomena. While continual monitoring does not result in improved track forecasts of an individual forecast cycle time compared with the single flight experiments, the main advantage of continuous monitoring is that all forecasts over the life of the TC show improved short-term forecasts.

As noted, vortex relocation was not used, nor were any TCVitals observations assimilated. Current operational practice uses vortex relocation, bogus wind observations, and the TCVitals estimates of central pressure and location; all of these might reduce the value of additional HALE UAS dropwindsonde data. When combined with vortex relocation and observations from manned flights, track improvements due to the use of UAS dropwindsonde data would be anticipated to occur in cases where the track error is influenced by initial condition errors in the vortex intensity or structure, or in the local steering flow.

Recent data impact experiments with a global plus limited-area ensemble Kalman filter (EnKF) data assimilation system demonstrate the importance in data assimilation for TCs of special observations, including TCVitals, scatterometer wind, and dropwindsonde data, provided that well-tuned robust quality control procedures are used (Holt et al. 2014, manuscript submitted to *Mon. Wea. Rev.*). As an alternative to vortex relocation, Nehrkorn et al. (2014a,b, manuscript submitted to *Mon. Wea. Rev.*) have developed and tested a feature alignment technique in a variational data assimilation system that could also prove useful in ensemble data assimilation systems. Ideally, vortex relocation would not be necessary in the presence of quality observational data, avoiding errors introduced during the artificial transplantation of the TC.

The main advantages of a HALE UAS compared to manned flights such as the G-IV for observing TCs stem from the extended range capabilities of the UAS. For example, the G-IV total flight time is approximately

8.5 h with no more than two flights per day, while HALE UAS can fly for more than 24 h per flight. The main constraint on frequent G-IV flights, in addition to the range of the aircraft, is the crew availability. The extended range allows the UAS to sample the TC during the early evolution of the cyclone, while the G-IV only observes TCs within 60 h of landfall. HALE UAS could sample a greater geographical region of the synoptic environment compared to manned missions as well.

The results presented here are confined to a case study of a single hurricane, and as such may not be broadly applicable. Observation impacts may differ if vortex relocation and/or manned aircraft observations are included in the data assimilation. The synoptic situation and source of forecast errors are different for every TC and each forecast per storm. Further studies should include the use of ensemble methods to produce more robust results.

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REFERENCES

Aberson, S. D., 2008: Large forecast degradations due to synoptic surveillance during the 2004 and 2005 hurricane seasons. *Mon. Wea. Rev.,* **136,** 3138–3150, doi:10.1175/2007MWR2192.1.

——, 2010: Ten years of hurricane synoptic surveillance (1997–2006). *Mon. Wea. Rev.,* **138,** 1536–1549, doi:10.1175/2009MWR3090.1.

Andersson, E., and M. Masutani, 2010: Collaboration on Observing System Simulation Experiments (Joint OSSE). *ECMWF Newsletter,* No. 123, ECMWF, Reading, United Kingdom, 14–16.

Braun, S., and Coauthors, 2013: NASA's Genesis and Rapid Intensification Processes (GRIP) field experiment. *Bull. Amer. Meteor. Soc.,* **94,** 345–363, doi:10.1175/BAMS-D-11-00232.1.

Errico, R. M., R. Yang, N. Privé, K.-S. Tai, R. Todling, M. Sienkiewicz, and J. Guo, 2013: Validation of version one of the Observing System Simulation Experiments at the Global Modeling and Assimilation Office. *Quart. J. Roy. Meteor. Soc.,* **139,** 1162–1178, doi:10.1002/qj.2027.

Harnisch, F., and M. Weissmann, 2010: Sensitivity of typhoon forecasts to different subsets of targeted dropsonde observations. *Mon. Wea. Rev.,* **138,** 2664–2680, doi:10.1175/2010MWR3309.1.

Kleist, D., D. Parrish, J. Derber, R. Treadon, W.-S. Wu, and S. Lord, 2009: Introduction of the GSI into the NCEP global data assimilation system. *Wea. Forecasting,* **24,** 1691–1705, doi:10.1175/2009WAF2222201.1.

Majumdar, S. J., and Coauthors, 2011: Targeted observations for improving numerical weather prediction: An overview. Tech. Rep., THORPEX Publ. 15, World Weather Research Programme, 37 pp.

——, M. Brennan, and K. Howard, 2013: The impact of dropwindsonde and supplemental rawinsonde observations on track forecasts for Hurricane Irene. *Wea. Forecasting,* **28,** 1385–1403, doi:10.1175/WAF-D-13-00018.1.

Nehrkorn, T., B. Woods, T. Auligné, and R. N. Hoffman, 2014a: Application of feature calibration and alignment to high-resolution analysis: Examples using observations sensitive to cloud and water vapor. *Mon. Wea. Rev.,* **142,** 686–702, doi:10.1175/MWR-D-13-00164.1.

Privé, N., Y. Xie, J. Woollen, S. Koch, R. Atlas, and R. Hood, 2013: Evaluation of the Earth Sytems Research Laboratory's Observing System Simulation Experiment system. *Tellus,* **65A,** 19011, doi:10.3402/tellusa.v65i0.19011.

Reale, O., J. Terry, M. Masutani, E. Andersson, L. Riishojgaard, and J. Jusem, 2007: Preliminary evaluation of the European Centre for Medium-range Weather Forecasts (ECMWF) nature run over the tropical Atlantic and African monsoon region. *Geophys. Res. Lett.,* **34,** L22810, doi:10.1029/2007GL031640.

Trahan, S., and L. Sparling, 2012: An analysis of NCEP tropical cyclone vitals and potential effects on forecasting models. *Wea. Forecasting,* **27,** 744–756, doi:10.1175/WAF-D-11-00063.1.